APPROVED FOR PUBLIC RELEASE

Safe-Escape Analysis System Safety Engineering Study

Kenneth Chirkis[1]
Naval Air Warfare Center, Weapons Division, China Lake, California, 93555

and

David H. Hall[2]
SURVICE Engineering Company, Ridgecrest, California, 93555

The Naval Air Systems Command (NAVAIR) contracted with SURVICE Engineering Company to review current technical requirements, approaches, assumptions and methodologies associated with the determination of safe-arming (minimum arm-time or arm distance) and safe-escape calculations and corresponding release conditions for air launched weapons systems. This paper reports the results of that study, comparing two Navy approaches: one at the Naval Air Warfare Center, Weapons Division (NAWCWD), China Lake, CA, and the other at the NAWC Aircraft Division (NAWCAD), Patuxent River, MD; the Air Force Seek Eagle Office approach at Eglin AFB, FL; and the Army approaches at the Aviation & Missile Research, Development & Engineering Center (AMRDEC) at Redstone Arsenal, AL. The study team conducted interviews with available Service experts; reviewed briefings and papers presented in various venues; and analyzed available M&S documentation. The study also drew on the results of the ongoing Joint Strike Fighter (JSF) effort to develop a Joint Safe Escape Analysis Solution (JSEAS). The comparison criteria included assumptions, requirements, definitions, aircraft modeling, weapon modeling, and the modeling and simulation suites used by the various Service commands. The paper concludes with recommendations for improvement in each of those areas.

Nomenclature

P_{hit} = Probability of Hit
P_{kill} = Probability of Kill

I. Introduction

Safe Separation analyses, Safe Arm analyses and Safe Escape Analyses are conducted as part of the system safety program for air weapons systems. These analyses are conducted for a variety of related purposes: to develop safe-arming times (or distances) to be designed into the weapon's safety and arming device; for a risk assessment as part of a safety of flight analysis; to determine safe escape maneuvers that may be required of the launch aircraft in order to meet safety requirements; to determine minimum safe weapon release altitudes; and to support safety of flight clearance for the weapon.

Currently, the Services use somewhat different approaches to conduct these analyses. These analyses are conducted at the Naval Air Warfare Center Aircraft Division (NAWCAD), Naval Air Warfare Center Weapons Division (NAWCWD), the Seek Eagle office at Eglin Air Force Base, the Aviation Engineering Directorate of the Aviation & Missile Research, Development & Engineering Center (AMRDEC) at Redstone Arsenal, and the AMRDEC System Simulation and Development Directorate, Endgame Analysis Branch. Past comparisons between the results of these analyses for Joint weapons systems have shown that in some cases the results from one Service activity derive release conditions that are restrictive or result in specific weapons capabilities not being authorized for use, whereas analysis by another Service activity may obtain a different result.

While NAWCAD and NAWCWD, for example, have specific commodities for which they are each responsible (powered weapons at NAWCWD and gravity weapons at NAWCAD), it is reasonable to expect approaches to be relatively consistent between the two organizations. In the past, attempts have been made to understand the

[1] Head, Systems Safety Branch, Code 416100D, Naval Air Warfare Center, Weapons Division
[2] Chief Analyst, SURVICE Engineering Company, 900E N. Heritage Drive

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED -
4. TITLE AND SUBTITLE **Safe-Escape Analysis System Safety Engineering Study**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Air Warfare Center, Weapons Division, China Lake, California, 93555**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM202644. AIAA Missile Sciences Conference Held in Monterey, California on November 18-20, 2008, The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

similarities and differences, but this effort has not been pursued to conclusion. With more Joint weapons entering service, it is imperative that release conditions be consistent among the services and that they provide effective employment tactics while maintaining adequate safety margins.

As a result of this issue, the Naval Air Systems Command (NAVAIR) contracted with SURVICE Engineering Company to review current technical requirements, approaches, assumptions and methodologies associated with the determination of safe-separation (minimum arm-time or arm distance) and safe-escape (weapons target impact) calculations and corresponding release conditions and to provide independent recommendations for improvement of this capability. This task was coordinated with the Weapon System Explosives Safety Review Board (WSESRB) and its associated sub-panels such as the Fuze and Initiation System Technical Review Panel (FISTRP) and Software System Safety Technical Review Panel (SSSTRP). SURVICE personnel attended the PMA-201 Fuze Integrated Product Team (IPT) System Safety Working Group (SSWG), as part of the system safety engineering support to program activities relating to requirements of the WSESRB. The results of this project were briefed to the Fuze Explosives Safety Working Group (FESWG) and the DOD Fuze IPT.

As a result of these efforts the FESWG has agreed to take responsibility for revisions and updates to the Joint Service agreements and standards for these analyses and the related definitions and methodologies.

II. Approach

The study plan consisted of the following tasks:

Develop Consistent Comparison Criteria: Develop a matrix of comparison criteria to use for conducting a detailed survey of the various approaches used at the various agencies involved. These criteria include methodology, data, and process issues.

Interview Service Safe-Separation/Safe-Arming Analysts: Meet with personnel involved in safe-separation and safe-escape analyses at each of the organizations to review all aspects of their methodology for performing safe-escape and safe-separation calculations against the comparison criteria. Of particular interest was whether any of the models used are formally accredited. This approach had to be modified when Air Force and NAWCAD personnel were not available to be interviewed. Where service personnel were not available for interview, the study participants attempted to fill in their information by interviewing other available experts in the field and reviewing previous briefings and reports. In addition, NAWCAD and Air Force personnel directed SURVICE to an ongoing project for the Joint Strike Fighter (JSF) program to develop a “Joint Safe Escape Analysis Solution (JSEAS)” for JSF.

Analysis of Interview Results: Compare the various Service methodologies using the comparison criteria. This analysis used the results of task 2 plus all other additional available information. The outcome of this task highlighted the differences in each of the methodologies.

Recommendations: Develop recommendations regarding best practices for safe separation/safe arming/safe escape analyses. These recommendations take into account the ongoing JSF JSEAS development, and include methodologies, data, processes, acceptable levels of risk, and standardized terminology.

Documentation: Document the results and present to the PMA-201 Fuze IPT System Safety Working Group, the Fuze Explosives Safety Working Group (FESWG) and the DOD Fuze IPT.

III. Discussion

Comparison Criteria: A set of consistent criteria were developed to compare the various approaches taken by the service facilities to conducting safe-separation/safe-arming analyses. These criteria were expressed in the form of interview questions having to do with:

1. **Assumptions:** assumptions made regarding launch aircraft maneuvers, both before and after weapon release; variations in weapon trajectory; environmental variations; launch modes; variations in safety and arming device functioning
2. **Requirements:** requirements used to evaluate weapon system safety (probability of hit, probability of kill, what values); whether post-launch maneuvers may be required to meet safety requirements; objectives of

the analyses (risk assessment only, determining safe-arm time/distance, safe escape maneuver, safety of flight clearance)

3. **Definitions:** terms used to describe the analyses, such as safe-separation analysis, safe escape analysis, safe arming analysis, etc.; what source documents describe those terms
4. **Aircraft Modeling:** how the launch aircraft is physically described (presented area, vulnerable area); what maneuvers are assumed before, during and after weapon release; how the launch aircraft flight path is determined; how the target flight path is determined (for air-to-air weapons)
5. **Weapon Modeling:** how the weapon's trajectory is modeled after release; how the warhead fragments and weapon debris are modeled, and how those data are obtained; how the safety and arming device is modeled; and whether debris from the target is included in the analysis
6. **M&S and Credibility:** safe-separation/safe-escape/safe-arming M&S used in conducting these analyses; what (if any) significant differences in capability exist between the various codes; what software accuracy (verification) documentation is available; what data accuracy documentation is available; what output accuracy (validation) documentation is available; whether the code has been accredited by any users; and what usability support (user groups or documentation) is available

In addition to these comparison criteria, the JSF JSEAS effort has resulted in a document that describes 23 criteria for a common safety analysis methodology for all air-to-ground weapons authorized for release by JSF. Those criteria were developed jointly between NAWCAD, the Air Force Seek Eagle Office, and the United Kingdom's Ministry of Defense (MOD). The JSEAS document compares some current approaches (Seek Eagle, NAWCAD, UK) for those 23 criteria, and documents the proposed JSF approach in each case. Since the JSEAS study as reported only applies to air-to-ground weapons (primarily gravity weapons), the criteria have a slightly different focus than originally envisioned for the study reported here, which includes air-to-air weapons as well. Also, the JSEAS criteria are not focused on M&S issues, but rather on joint safety criteria. As a result, the JSEAS criteria are more comprehensive than the questions developed for this study when describing air-to-ground weapon safety criteria, but they do not mention M&S criteria, nor address air-to-air or powered weapons specifically. They also do not address assumptions about target maneuvers, or risks from enemy weapons.

Assumptions

The assumptions made about aircraft maneuvers, variations in weapon characteristics, safety and arming device function and any parameters that are unknown quantities can often be significant drivers of the results of this type of analysis. We were unable to obtain much information about the general assumptions made by NAWCAD, but it appears that the Seek Eagle Office and the NAWCWD analysts generally make similar assumptions in these areas, and have come to some agreement on general approaches for powered air weapons systems. They generally assume that straight and level flight of the launch aircraft is the "worst case" scenario from a safety standpoint, since in that case the aircraft is following behind the weapon. That assumption may not hold, of course, for air-to-air weapons where the target is maneuvering, or for off-boresight launch. For air-to-air weapons, varying after-launch fixed-g maneuvers are evaluated. Launch altitudes and speeds are chosen from tactics manuals, which is likely to be the case with analyses conducted by all the Service agencies. Variations in weapon trajectory are handled by varying launch modes, weapon angle of attack and motor temperature (where data are available). And the assumed arming time/distance takes into account the tolerances on fuze design.

The Army approach seems to be focused on specific low-altitude launch tactics for helicopters against ground targets: hover, bank, dive, break turns toward masking terrain after launch, or vertical and/or horizontal unmask, then re-mask and egress after launch. For the Army, the minimum safe range is a combination of altitude and down range from the helicopter to its ground target. Army helicopters normally fire weapons from 30ft to 150ft altitude and airspeed between hover and 90 knots. For running cases (level flight or diving), the common practice after releasing the weapon is either veer to the left or veer to the right and avoid the target.

Requirements

There are some known differences between the requirements used by the various service agencies that conduct these analyses. One significant difference between the Seek Eagle Office and NAWCWD is that the Navy analysts

consider probability of kill (P_{kill}) of the launch aircraft as a fallback metric to probability of hit (P_{hit}). It appears that the UK also uses a similar metric to P_{kill} in their "self-damage" probability, and the Army allows for calculation of P_{kill} as part of their risk assessment process. While P_{kill} (or self damage) as a metric is less conservative from a safety standpoint than P_{hit}, it follows the guidelines of the original Joint Fuze Management Board Agreement on safe separation analysis requirements[3]. This approach is best described by a graphic from a NAWCWD viewgraph presentation[4], shown in Figure 1.

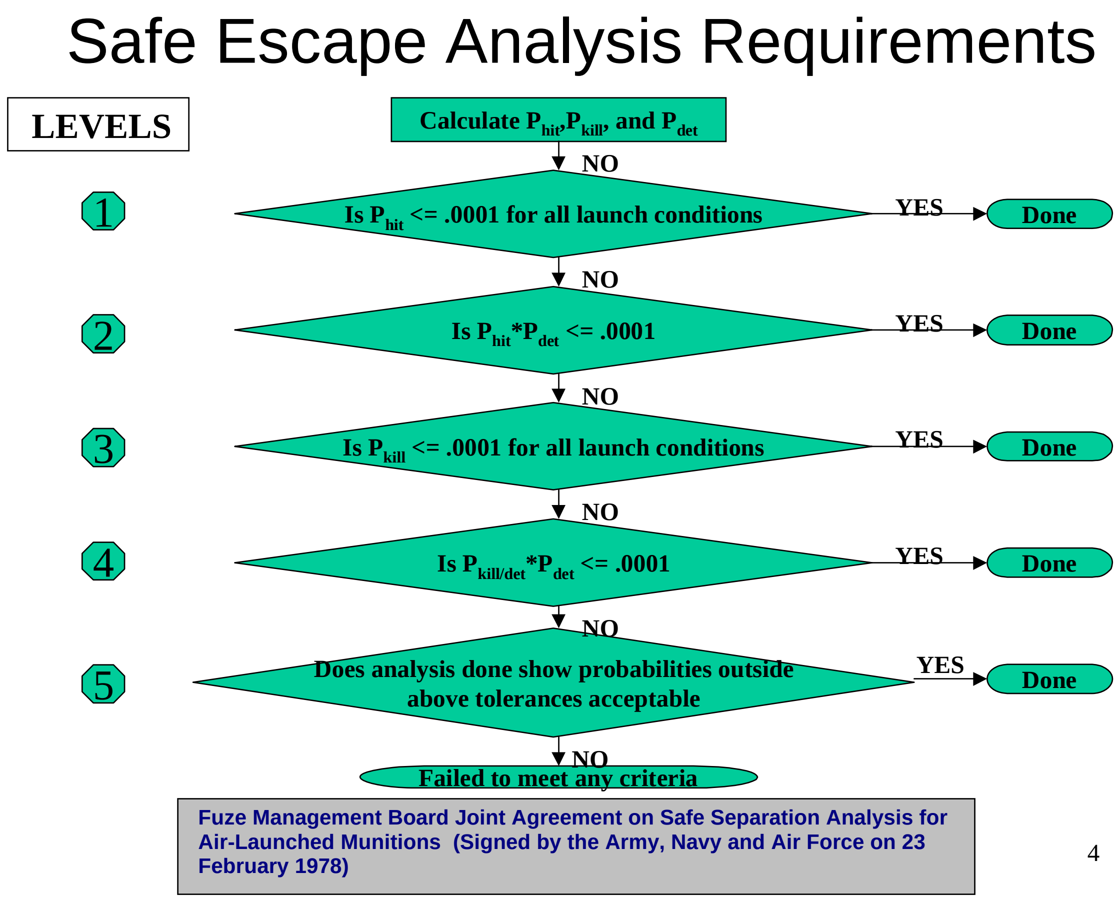


Figure 1. Safe Escape Analysis Requirements

The process is a series of questions: if the probability of hit is below the one-in-ten-thousand threshold, then the system meets the basic requirement. If that is not the case, if the probability of hit (given detonation at or after arming) multiplied by the probability of detonation at arming is less than .0001, then it meets the threshold. In Figure 1, P_{det} is defined as the probability of detonation at arming and cannot be less than .01 for this calculation.

If neither of those conditions is met, then probability of kill is substituted for P_{hit}. The following language in the Joint Fuze Management Board Agreement justifies this approach:

---

[3] *Fuze Management Board Joint Agreement on Safe Separation Analysis for Air Launched Munitions*, 23 Feb 1978
[4] *Safe Escape Analysis Overview*, Naval Air Systems Command (NAVAIR) Warfare Analysis Department, Systems Division, AIR 4.10.2, 18 August 2003

> "If the minimum safe-separation distance resulting from the above procedure restricts tactical delivery conditions, the probability of a fragment hit may be further qualified by considering only the presented area of critical systems or components rather than the area of the complete launching system."[5]

The NAWCWD approach interprets "probability of hit on presented area of critical systems or components" to be represented by P_{kill}. If the system still does not meet the criterion using P_{kill}, then the Joint Agreement allows for an analysis of other risks and hazards; for example, with an air-to-air weapon, if the arm time is too long, there is some risk that the enemy aircraft may be able to launch a weapon inside our weapon's minimum range. Thus the hazard from enemy weapons may exceed the hazard from our own weapon, and justify a shorter arm time. The actual wording in the Joint Agreement on this subject is as follows:

> "If the above procedures still result in restricting tactical delivery conditions, then selected fuze arming conditions which are such that a safe-separation distance is not achieved must be justified by a thorough analysis. This analysis should consider probability of a specific type of damage, decreased risk from enemy ordnance, and tactical advantage gained by use of the recommended fuze arming characteristics…The results of this analysis will be included in the final safe-separation analysis report and the tactical manuals will identify those fuze arming conditions which, for given delivery conditions result in specified hazards to the launching system."[6]

The Seek Eagle office does not follow this approach; their analysts use only P_{hit} as a metric. From anecdotal evidence it appears that the same is true of NAWCAD analysts.

It should be noted that a "fragment hit" is defined in the Joint Agreement as:

> "A fragment which contains sufficient kinetic energy to penetrate the launch aircraft skin which is exposed to the hazard. Caution must be exercised <u>not</u> to eliminate from the calculations those low relative velocity fragments which may cause serious damage if ingested by the engine(s)."[7]

Other than the Army, it is not clear whether the service agencies that conduct these analyses restrict fragment sizes and velocities to those conditions when calculating probability of hit. Anecdotal evidence seems to indicate that very small fragment sizes are included in most of these analyses, which could result in overly conservative risk assessments. The Army, on the other hand, restricts the hit analysis to only include fragments with kinetic energy of 5 ft-lbs or more relative to the aircraft, or for which the striking velocity is above V_{50} (velocity at which half of the fragments penetrate the aircraft skin) – the two different criteria are used by the two different directorates at AMRDEC that conduct these analyses.

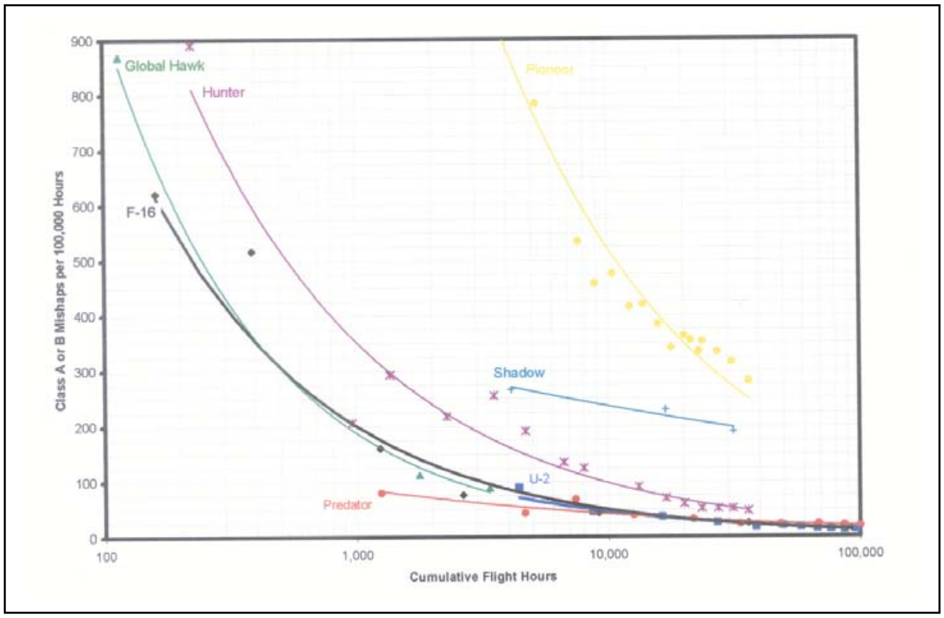
Based on the results of safe escape/safe arming analyses conducted by NAWCWD, there have occasionally been post-launch maneuver requirements placed on the launch aircraft in order to meet the safety criterion. (Safe escape analyses conducted for air-to-ground weapons also may determine a minimum safe release altitude). This is only true for air-to-ground weapons, as opposed to air-to-air weapons. There is some evidence that this is also the case for Seek Eagle, UK and NAWCAD analysis results. It is unknown whether the Army places similar restrictions on their weapons delivery helicopters. A briefing to the FESWG by AMRDEC analysts from the System Simulation

[5] *Fuze Management Board Joint Agreement on Safe Separation Analysis for Air Launched Munitions*, 23 Feb 1978, Page 3, paragraph 4b
[6] Ibid, Page 4, paragraph 4d
[7] Ibid, Page 1, paragraph 2c

and Development Directorate seems to indicate that they do not place such restrictions[8]. That briefing also confirms that the AMRDEC analysts from that directorate use the one in ten thousand probability requirement.

The requirement for probability of hit (or kill) being less than one in ten thousand seems to have been based on historical loss rates and/or mishap rates from the era of the Vietnam conflict. The initial analysis of that data appears to have been reported in a letter dated in 1973, which led to the eventual signing of the Joint Fuze Management Board Agreement in 1978. We were unable to retrieve a copy of the 1973 letter; however, a more recent analysis of mishap rates for both tactical aircraft and unmanned aircraft was reported in the UAS Roadmap 2005[9]. Figure 2, reproduced from that document, shows mishap rates for F-16, Global Hawk, Predator and other unmanned aircraft systems (UAS) as a function of cumulative flight hours. For the F-16 and the Predator, which both have over 100,000 flight hours logged, the mishap rate appears to be on the order of ten mishaps per 100,000 flight hours; most of the other systems seem to be converging on a similar mishap rate as their cumulative flight hours increase.

Figure 2. Mishap Rate Comparison



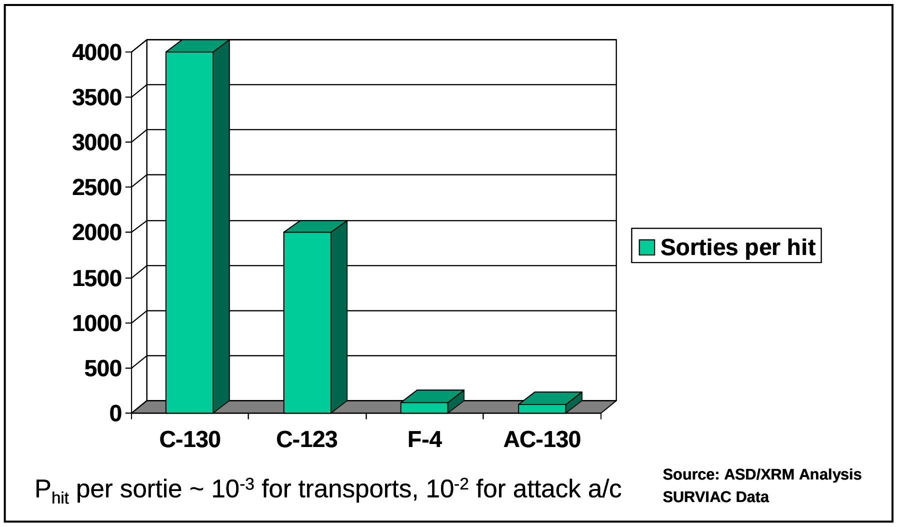
It is difficult to reconstruct data on probability of hit by threat action for the Vietnam era (or for more recent conflicts, for that matter). One analysis done by the Air Force using data from the Survivability/Vulnerability Information Analysis Center (SURVIAC) shows that USAF aircraft hit rates per sortie in Vietnam ranged from one in 100 (for F-4 and AC-130 aircraft) to one in 4,000 (for the C-130): see Figure 3. The wide range in probability of hit is explained by the fact that the relative exposure of the aircraft to threat systems varied considerably by mission in that conflict. Gunships and fighters were far more likely to be directed to areas where they encountered threat systems than were transport aircraft. For none of the aircraft of that era was the probability of hit per sortie less than two in 10,000: they tended more toward one in 100 or one in 1,000[10].

[8] *Safe Separation Analysis*, Kim Williams, Shane Strickland, Brent Deerman, 30 Nov 2005

[9] *Unmanned Aircraft Systems Roadmap 2005-2030, Office of the Secretary of Defense, 4 Aug 2005*

[10] *Historical Combat Data*, briefing given by Kevin Crosthwaite, Director, Survivability-Vulnerability Information Analysis Center (SURVIAC), Aircraft Survivability Short Course, 11-13 July 2006

Figure 3. Sorties Per Hit in South-East Asia



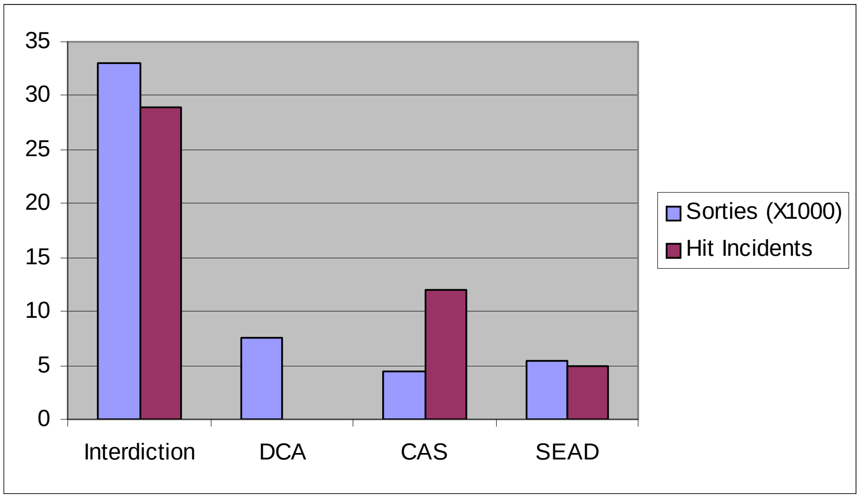
We obtained a report by the Center for Naval Analyses that reported Vietnam combat damage incidents and aircraft kill rates for USN and USMC fixed wing aircraft[11]. In that report, the damage incident and kill rates for USN aircraft were 2,147 damage incidents and 538 loss incidents per 512,757 sorties, or a hit rate of 5.23 per 1000 sorties and a kill rate of 1.05 per 1000 sorties. For USMC aircraft, there were 1,871 damage incidents and 173 kills in 323,542 sorties, or hit rate of 6.32 per 1000 sorties and a kill rate of 0.54 per 1000 sorties (note that damage incidents plus kills add up to hit incidents). These data were for the period from April 1965 through March 1973. Thus, the overall average hit rates were on the order of one hit per 100 sorties, and the kill rates on the order of one loss per 1000 sorties.

Another analysis by SURVIAC of aircraft hits during Desert Storm[12] (see Figure 4) indicates that hit rates in that conflict also varied by mission type: for interdiction missions, there were about 30 hits in 33,000 sorties (about one in 1,000); for close-air-support (CAS) missions, there were 12 hits in fewer than 5,000 sorties (about one in 400). Suppression of Enemy Air Defense (SEAD) missions resulted in 5 hits for approximately 5,000 sorties (one in 1,000), whereas Defensive Counter Air (DCA) missions resulted in no hits for 7,500 sorties (because there were virtually no air-to-air threats that would fly in that conflict). This analysis seems to imply that the hit rate due to hostile action during Desert Storm was on the order of one hit in 1,000 sorties.

[11] *U.S. Navy, Marine Corps and Air Force Fixed Wing Aircraft Losses and Damage in Southeast Asia (1962-1973)*, Michael M. McCrea, Center for Naval Analyses, CRC 305, August 1976

[12] *Mission & Campaign Analysis*, briefing given by Kevin Crosthwaite, Director, Survivability-Vulnerability Information Analysis Center (SURVIAC), Aircraft Survivability Short Course, 11-13 July 2006

Figure 4. Hits During Desert Storm by Mission Type



P_{hit} per sortie ~ 10^{-3}
(or zero, for DCA – no threat a/c)

Source: SURVIAC

Comparing either mishap rates (per flight hour) or probability of hit during historical conflicts (per sortie) to probability of being hit by your own weapon given launch is really comparing apples and oranges. We have mishaps per flight hour; threat hits per sortie; and in the safe escape/safe separation case, fragment hits per weapon launch. However, in a system safety sense, both mishap rate and combat hit rate provide some measure of how "safe" each of these activities are: in the one case, what are historical "acceptable" mishaps during flight operations, and in the other what are the historical hit rates that have been tolerated each time an aircraft is sent on a mission. As such, they provide at least a qualitative measure of accepted safety levels.

Using probability of hit less than 0.0001 as a safety criterion seems to be a reasonable fit with historical mishap rate data and with more recent data as reported for both manned and unmanned systems. It is less consistent with combat hit rates per sortie, which are on the average at least an order of magnitude higher (one in 1,000 for Desert Storm, and for USN and USMC fixed wing aircraft in Vietnam, closer to one in 100). Those higher combat hit rates do, however, provide justification for considering an analysis of "…probability of a specific type of damage, decreased risk from enemy ordnance, and tactical advantage gained by use of the recommended fuze arming characteristics…" in the system safety assessment, as allowed by the Joint Fuze Management Board Agreement. If the hit (or kill) probability does not meet the one in 10,000 requirement, then an analysis of other risks to the system should be conducted to determine if they out-weigh the risk of damage from launching our own weapon. Historically, those hit rates from threat weapons have been much higher.

Definitions

Much confusion has resulted from multiple definitions of terms in this area over the last 30 years and more. "Safe Separation" in particular has been used for more than one purpose. "Safe separation" has been taken to mean both safe release of the weapon from its launcher, and that the weapon is a safe distance away from the launcher at the time the fuze arms the warhead. Those are two completely different concepts, but have both been called the same thing in the past. Official documentation doesn't seem to help the problem, as can be seen from the published definitions below:

Definition from MIL-HDBK-1763[13]:

> **Safe Separation:** The parting of a store(s) from an aircraft without exceeding the design limits of the store or the aircraft or anything carried thereon, and without damage to, contact with, or unacceptable adverse effects on the aircraft, suspension equipment, or other store(s) both released and unreleased.

Definition from MIL-STD-1316E[14]:

> **Safe Separation Distance:** The minimum distance between the delivery system (or launcher) and the launched munition beyond which the hazards to the delivery system and its personnel resulting from the functioning of the munition are acceptable.

Definition from the Joint Agreement[15]:

> **Safe-Separation Distance:** the minimum distance between the launching system (AIRCRAFT & PILOT) and its launched munitions at which hazards associated with munitions functioning are acceptable. This distance may be achieved by providing arming delays(s) (time or distance).

It could be argued that the MIL-HDBK definition of "safe separation" is distinct from the two (similar) definitions of "safe separation distance". However, the use of the words "safe separation" in all three definitions is the cause of the confusion, especially when assessments of the two have been called "safe separation analysis" in the past.

With regard to definitions, some of the service experts now use "Safe Escape Analysis" to describe the work they do in arriving at risk assessments for air-to-air weapon systems. The details of that analysis differ, however, from safe escape analyses conducted for air-to-ground weapons. Seek Eagle and NAWCAD analysts define safe escape analysis as producing a Minimum Release Altitude (MRA) consistent with a maximum probability of hit threshold; MRA is termed Minimum Safe Release Altitude for Fragment Avoidance, or MinAlt by NAWCAD. NAWCWD, on the other hand, uses the term "safe escape analysis" to refer to an assessment of the risk of launching an air weapon, and does not refer to a minimum safe release altitude, probably since NAWCWD only analyzes powered weapons. The AMRDEC analysts define "safe escape analysis" as "determining the minimum safe range for helicopters to release weapons." They also feel that any definition of "Safe Escape" should include both altitude and down range, since to them the minimum safe range is a combination of altitude and down range from the helicopter to its ground target.

MIL-HDBK-1763 provides a definition for safe escape that may be part of the solution, but that still concatenates the two terms "safe escape" and "safe separation":

> **Safe Escape/Safe Arming:** Safe escape is the minimum release altitude that will provide the delivery aircraft acceptable protection from weapon fragmentation for detonation at the preplanned point. Safe arming separation is the selection of a minimum safe fuze arm time setting that will provide the delivery aircraft acceptable protection from weapon fragmentation if early detonation should occur.

Aircraft Modeling

Probability of hit on the aircraft by weapon debris fragments is calculated using a simple six-view "box" representation of the presented area of the aircraft. This is true of all the approaches used by the services, except

---

[13] *Aircraft/Stores Compatibility: Systems Engineering Data Requirements And Test Procedures*, MIL-HDBK-1763

[14] *Department of Defense Design Criteria Standard, Fuze Design, Safety Criteria Fo*r, 10 July 1998, MIL-STD-1316E

[15] *Fuze Management Board Joint Agreement on Safe Separation Analysis for Air Launched Munitions*, 23 Feb 1978, Page 1, paragraph 2a

that the AMRDEC process provides for a second pass with a detailed CAD model of the aircraft: their first pass with the “shoe-box model” is intended to compute “potentially-hit-fragments”. Since their approach is a set of one million Monte-Carlo iterations of the warhead detonation, the initial screening pass is needed to reduce the computations required for the detailed CAD model of the aircraft to only those fragments with some probability of actually hitting it. The second pass actually calculates the probability of hit on the aircraft.

For the NAWCWD approach to determining probability of kill, the presented areas are replaced by six-view vulnerable areas obtained from vulnerability analyses conducted by the NAWCWD Survivability Division for the launch aircraft in question. Vulnerable area is defined as probability of kill given a hit multiplied by presented area; consequently, it is an “expected value” approach to describing system vulnerability. In a way, it represents the presented area of critical components and systems. Vulnerable area is a function of fragment size and striking velocity.

In the case of air-to-air weapons, NAWCWD analysts assume that straight and level flight for the target aircraft is the worst case, since in that case the launch aircraft is most likely to follow directly behind the weapon. NAWCWD and Seek Eagle analysts use the JTCG/ME Joint Air-to-Air Model (JAAM) to develop flight paths for both launch aircraft and target aircraft (for air-to-air weapons). In addition, for the Air Force the Aircraft/Weapon Delivery Software (AWDS) library can be used with CASES to develop aircraft flight paths. No information was available on NAWCAD aircraft trajectory modeling. For AMRDEC analyses, flight data (aircraft velocity components and orientation) are generated with RCAS or FlightLab, both of which are high fidelity helicopter simulation software.

Weapon Modeling

For the NAWCWD and Seek Eagle analyses, the trajectory of the weapon is almost always provided by the weapon systems program office, either directly or via delivery of their weapon flight simulation; for powered weapons the simulation is almost always a six degree-of-freedom simulation, providing position, yaw, pitch and roll as a function of time after launch. The Seek Eagle approach also allows for weapon trajectories to be developed by the AWDS dynamically linked library as part of CASES. For the Army, weapon trajectories are provided by program office 6-dof simulations and input into the ADAMS software.

Generally speaking, the weapon trajectory simulations provided by the program office responsible for the weapon’s development are considered to be “ground truth” and are usually rigorously validated, even if those validation data are not always documented or retrievable.

Weapon system debris fragments and warhead fragments are modeled using polar (and in some cases azimuth) zones, usually with constant fragment ejection velocity over the zone and an average number of fragments per zone. The size of the fragment zones depends on the quality of the arena test data for the specific weapon in question; generally 10-degree polar zones are used, and occasionally the data will allow for 5-degree polar zones. CASES allows a maximum of 18 polar zones and exactly 24 roll zones (of 15 degrees). For most systems, the fragment zones are symmetric around the body of the weapon. It is possible to conduct separate analyses for fragments of unusual size and/or velocity (warhead fragments, for example, or bomb lugs), and combine the results of that analysis with the main body of fragments into an aggregate result. Gamma zones are the mechanism that accounts for fragment size and shape, where gamma is the ratio of a fragment’s average presented area to its mass.

Without discussing this in person with the individual service experts, we were not able to determine with what fidelity all service weapons debris patterns are modeled. However, we did obtain a briefing and paper that were presented at an April 2006 Seek Eagle conference that describes the approach used for Seek Eagle fragmentation test data collection and analysis[16]. That paper described the use of a computer-driven Fragment Digitizer System that greatly facilitates development of fragment shape factors, presented areas, and gamma values. The weapon debris model is a principal driver of the results of the safe escape/safe arming analysis.

---

[16] *Common Advanced Safe Escape System (CASES): A Look Behind the Scene*, Tommy Collins, James Burton, Shane Sartalamacchia, Tama Leach

The Army briefing from the Seek Eagle conference[17] shows example polar zones for a 2.75 inch rocket (M151 Warhead and rocket debris); the data in the briefing show 5-degree polar zones, and those are assumed to be representative of the fidelity of Army system debris models.

M&S and Credibility

NAWCAD, NAWCWD and Seek Eagle all use safe escape models and simulations that have common heritage. NAWCAD uses Path 4, NAWCWD uses the Advanced Safe Escape Program (ASEP), and Seek Eagle uses the Common Advanced Safe Escape System (CASES), all of which have their origins in the development of Path 2 by the Navy at Dahlgren, VA. Path 4 is an evolution from Path 2, Path 3D was an evolution from Path 2, ASEP is an evolution from Path 3D, and CASES is an evolution from ASEP.

All of those methodologies use similar (if not the same) representations of missile debris and warhead fragments, fragment flight paths, calculations of probability of hit (and kill), and launch aircraft representations. There are some capabilities that have been added with each evolution of the code: for example, CASES appears to be ASEP with a better Graphical User Interface (GUI) and some pre-generated warhead data files for certain weapons. It also allows for calculation of "deconfliction", meaning that it will determine whether fragments can hit another aircraft in the same flight as the launch aircraft. ASEP added asymmetric fragment roll zones to PATH-3D along with some other improvements.

There has been no organized effort to conduct and document verification and validation on any of the codes. There have been comparison runs made between CASES and ASEP, with some minor errors corrected as a result of those runs; however, there is no documentation available of those comparisons or the changes that were made as a result. There is anecdotal evidence that the Seek Eagle office has accredited both CASES and ASEP for individual weapons systems analyses, but no documentation of those accreditation decisions was available.

The Seek Eagle office provides limited support to users of both ASEP and CASES. A User Manual[18] and Analyst Manual[19] are available for ASEP. It is unknown what documentation is available for CASES or for Path 4.

The Army analysts at AMRDEC use a set of simulations that were developed independently from the Seek Eagle set of models. They use the Army Safe Escape Analysis Tool (ASEAT), which includes several additional software packages: ADAMS, EASY5, FlightLab, 3D-CAD and weapon fly-out models. ADAMS is the 6-dof simulation used for aircraft flight paths and fragment trajectories. EASY5 is a system-level modeling tool used for describing the physical components of the aircraft system, such as hydraulics, controls and electrical subsystems. The 3D-CAD simulation provides a detailed physical description of the aircraft that is used in the final P_{hit} calculation. ADAMS, EASY5, and FlightLab are commercial software. RCAS and weapons 6-dof are the Army's software.

If there is a need to fire the munition at a target at a range closer than the minimum safe range, then P_{kill} can be calculated as a safety metric with a simulation such as the Advanced Joint Effectiveness Model (AJEM). P_{kill} is an important piece of information used in conducting risk assessments for the Army Airworthiness Qualification and Release processes.

The primary differences between the AMRDEC and Seek Eagle simulations is that the AMRDEC approach uses a one-million iteration Monte Carlo simulation of weapon debris fragmentation, and a two-pass calculation of probability of hit (to reduce run-time). The Seek Eagle models, on the other hand, use an expected value approach, computing an expected number of fragments in each polar-azimuth zone. The Army P_{hit} calculation also uses a detailed CAD model of the aircraft, whereas the other methodologies use a simple six-sided representation of the aircraft's presented area. It is not clear whether the fidelity of the weapon debris data obtained from arena testing is consistent with the detail available in CAD models of the aircraft. It may be that the shorter range weapons

[17] *Safe Escape for the Army Helicopters*, Tuan Pham, Aviation & Missile Research, Development & Engineering Center, Aviation Engineering Directorate, Weapons & Sensors Branch, April 2006
[18] *Advanced Safe Escape Program (ASEP) Users Manual*, ASEP-UM-002, December 1996, Tybrin Corporation
[19] *Advanced Safe Escape Program (ASEP) Analysts Manual*, ASEP-AM-002, December 1996, Tybrin Corporation

employed by the Army result in close enough detonations to justify the need for the additional fidelity in the aircraft model.

There is no documented verification, validation or accreditation of the ASEAT set of simulations, nor is there documentation available for ASEAT.

IV. Conclusions

Assumptions: There was very little information available about assumptions made by analysts other than those at NAWCWD. Since these assumptions can drive the answers, it is important that they be consistent across the service agencies that conduct these analyses.

Requirements: The requirement for probability of less than one in ten thousand appears to be consistent with historical mishap rates (per flight hour), but it is not as consistent with combat hit rates (per sortie), which are an order of magnitude higher. The principal difference between the service agencies in requirements is the use of P_{kill} as a fallback metric to P_{hit}. Analysts at NAWCWD use probability of kill (and the UK analysts use something similar), and AMRDEC uses P_{kill} as part of their risk assessment process, but it appears that Seek Eagle and NAWCAD strictly use P_{hit}. The JSEAS project has put considerable effort into examining requirements across the services and coming up with common requirements for the JSF program. That project has not involved the Army, however, since there is no Army variant of JSF. Consequently, the requirements developed by JSF only apply (so far at least) to the Navy (and by extension the Marine Corps) and the Air Force. Also, the JSEAS requirements document states that they only apply to air-to-ground weapons (with an apparent emphasis on gravity weapons).

Definitions: The use of the term “safe separation analysis” to mean more than one thing causes considerable confusion, especially for weapons system program offices who may think they’ve met a requirement only to find that they only addressed another issue entirely.

Aircraft Modeling: Aircraft presented area seems to be modeled in the same way by all of the services, using a six-view total presented area (the Army adds a detailed CAD model of the aircraft for their final P_{hit} calculation). NAWCWD analysts also use six-view vulnerable area to represent “the presented area of critical components and systems”. AMRDEC allows for using a model like AJEM for a detailed P_{kill} calculation. Aircraft flight paths for NAWCWD and Seek Eagle are based on the JTCG/ME JAAM methodology; AMRDEC uses RCAS or FlightLab.

Weapon Modeling: Weapon trajectories are usually generated using program office 6-dof flight simulations for powered weapons systems. We were unable to obtain information about NAWCAD approaches to gravity weapons modeling or with what fidelity weapon fragmentation is usually modeled at NAWCAD.

M&S and Credibility: NAWCWD, NAWCAD and Seek Eagle all use M&S which evolved from the same original source, Path-2, which was developed originally by the Navy at Dahlgren, VA. Based on anecdotal evidence, the differences between these codes seem to be minor compared to the similarities. There is no available documentation of past verification and validation activities. We were only able to obtain documentation of the ASEP model used at NAWCWD. Seek Eagle has apparently accredited ASEP and CASES for some applications, but documentation of those accreditation decisions was not available. The Army uses an independently developed methodology called ASEAT, which is a Monte Carlo simulation, and uses detailed representations of the launch aircraft’s geometry. There is no documentation of any past VV&A results for ASEAT.

V. Recommendations

Assumptions: There should be Joint Service guidelines for the assumptions made in conducting safe escape/safe arming analyses. In particular, guidance should be provided regarding launch aircraft maneuvers, weapon variations (angle of attack, motor temperature, roll orientation, etc.), environmental factors, safe-arm device variations, and other factors that potentially drive the analysis results.

Requirements: The JSEAS document provides a comprehensive set of requirements for air-to-ground weapons safe escape analyses that have been accepted by the participants in JSF. Those requirements should serve as the starting point for expansion to include Army requirements and air-to-air weapon system requirements, and to ensure that all powered air-to-ground weapon requirements are adequately treated. Provision should be considered in future Joint requirements for application of the process outlined in the original Joint Agreement between all the services, particularly the inclusion of P_{kill} as a metric and the provision for additional analyses to support operational use of weapons that do not meet the 0.0001 probability requirement. Historical combat hit rates offer justification for those additional analyses. Requirements for safe escape (minimum safe release altitude) and safe arming/safe separation (maximum hazard to the launch aircraft at and after arming) should be consistent.

Definitions: A possible solution to the definitions problem is to divide the definition of "Safe Escape/Safe Arming" that is offered in MIL-HDBK-1763 into separate definitions for the two terms. The term "safe separation" should only refer to the safe release of the store from the aircraft. This change also would mean that the definitions of "safe separation distance" in both MIL-STD-1316E and in the original Joint Fuze Management Board agreement should be changed to "safe arming distance". Draft definitions are as follows:

> **Safe escape:** Safe escape is the required release conditions and post-launch maneuvers that will provide the delivery aircraft acceptable protection from weapon fragmentation for detonation at the preplanned point, or at or after arming; this may result in a minimum safe release altitude or safe release altitude and down range from the target.
>
> **Safe arming:** Safe arming is the selection of a minimum safe fuze arm setting that will provide the delivery aircraft acceptable protection from weapon fragmentation if detonation should occur at or after the fuze arm time/distance.
>
> **Separation:** The termination of all physical contact between a store, or portions thereof, and an aircraft; or between a store, or portions thereof, and suspension equipment.
>
> **Safe separation:** The parting of a store(s) from an aircraft without exceeding the design limits of the store or the aircraft or anything carried thereon, and without damage to, contact with, or unacceptable adverse effects on the aircraft, suspension equipment, or other store(s) both released and unreleased.

Aircraft Modeling: There should be agreed-upon guidelines for launch aircraft post-launch maneuvers to consider for safety reasons. Sensitivity analyses should be conducted to determine whether there is a need for more detailed aircraft representations than 6-view presented areas (as in the AMRDEC approach).

Weapon Modeling: There should be agreed-upon guidelines for the fidelity of weapon debris modeling (polar zones, etc.). Guidelines should be established for when to segregate "unusual" fragments for separate analysis (such as bomb lugs, warhead fragments that are likely to have much higher velocities than debris fragments, etc.). Fragments should only be included in the weapon debris model if they are capable of penetrating the skin of the aircraft (per the Joint Agreement definition of "fragment hit", and consistent with the Army's KE>5 ft-lbs or striking velocity>V_{50} requirement for fragment inclusion in the debris model).

M&S and Credibility: Navy representatives should consider migrating to the latest version of the Seek Eagle methodology (CASES). When available, the JSEAS methodology should be assessed for adoption as the standard Joint Service methodology. Documented verification and validation evidence should be developed for any M&S tools used in safe escape/safe arming analyses. Documentation of all methodologies used by the services should be developed, maintained and distributed to users. An Accreditation Support Package (ASP) should be developed for any M&S tools that are continuing in use.